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The Seto Inland Sea—eutrophic or oligotrophic?

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Abstract

The present water quality conditions in the Seto Inland Sea of Japan are described along with an historical background before and after the measures taken to reduce eutrophication. The directive to reduce phosphorus discharge into this area was very effective, reducing the number of red tides from about 300 cases per year at their peak in 1976 to the recent level of about 100 cases per year, indicating the improvement of seawater quality. However, the hastiness of the measures taken to reduce phosphorous seems to have led to a depletion of dissolved inorganic phosphorus that is an essential nutrient for the growth of phytoplankton. Fishery production has also decreased with the reduction of phosphorus, showing a time lag, and the relationship between them shows a hysteresis-like pattern indicating that the condition of fishery production is currently in a critical stage of collapse. This implies that the phosphorus reduction could have lowered the phytoplankton primary production and also caused a detrimental effect on the fishery production. Noteworthy is the change in the phytoplankton species composition. The dominant species that form red tides have changed from non-harmful diatoms to harmful raphidophytes in the eutrophication process and then finally to harmful/toxic dinoflagellates in the oligotrophication process. This indicates that the measures to reduce phosphorus have caused a change in phytoplankton species composition, thereby altering the food web structure, suggesting that this might be the major cause of the reduction of fishery production. In conclusion, the Seto Inland Sea of Japan is apparently in an oligotrophic condition, and it could be said to be in the state of "cultural oligotrophication" caused by the hasty reduction of phosphorus loading. Dam construction, as another possible cause of the cultural oligotrophication, is also discussed, and evidence relating to the existence of numerous dams in this area is also shown. Stress is placed on the regulation of the level of nutrients and their elemental ratio in the seawater, because these factors are considered to be effective in preventing the generation of harmful algae and in sustaining the fishery production through preservation of the natural environment. A proposal is also described regarding how these factors could be controlled.

Keywords: Dam; Eutrophication; Fisheries; Oligotrophication; Seto Inland Sea; Sewage

1. Introduction

Eutrophication processes in lakes and coastal waters have been the subjects of intensive study. Eutrophication in coastal areas has affected fish cultures and other activities through the occurrence of red tides. Most eutrophication is a result of anthropogenic activities such as industrialization and urbanization. Therefore, this type of eutrophication has been called "cultural eutrophication" (Edmondson, 1969).

On the other hand, in recent years there have been signs of oligotrophication in some lakes of developed countries (Sas, 1989). In contrast to "cultural eutrophication", this phenomenon has been called "cultural oligotrophication" by Stockner et al. (2000). Among several possible causes of the cultural oligotrophication of freshwater systems proposed by Stockner et al. (2000), two of them are considered to be specifically applicable to estuaries. One is an excess removal of nutrients from the discharged water of sewage treatment plants (STPs), and another is the impoundment of rivers by dams. Dams also reduce the nutrients in the discharged water, because they trap nutrients as particulate forms on the bottom of reservoirs as a result of sedimentation of bloomed phytoplankton in the water column (Humborg et al., 1997, 2000).

The Seto Inland Sea is the largest estuary located in the western part of Japan, with a size of $\approx$23,000 km^2 and an average depth of $\approx$38 m (Fig. 1). In this area, with an increase in human activities expressed by industrialization and urbanization, the processes of eutrophication

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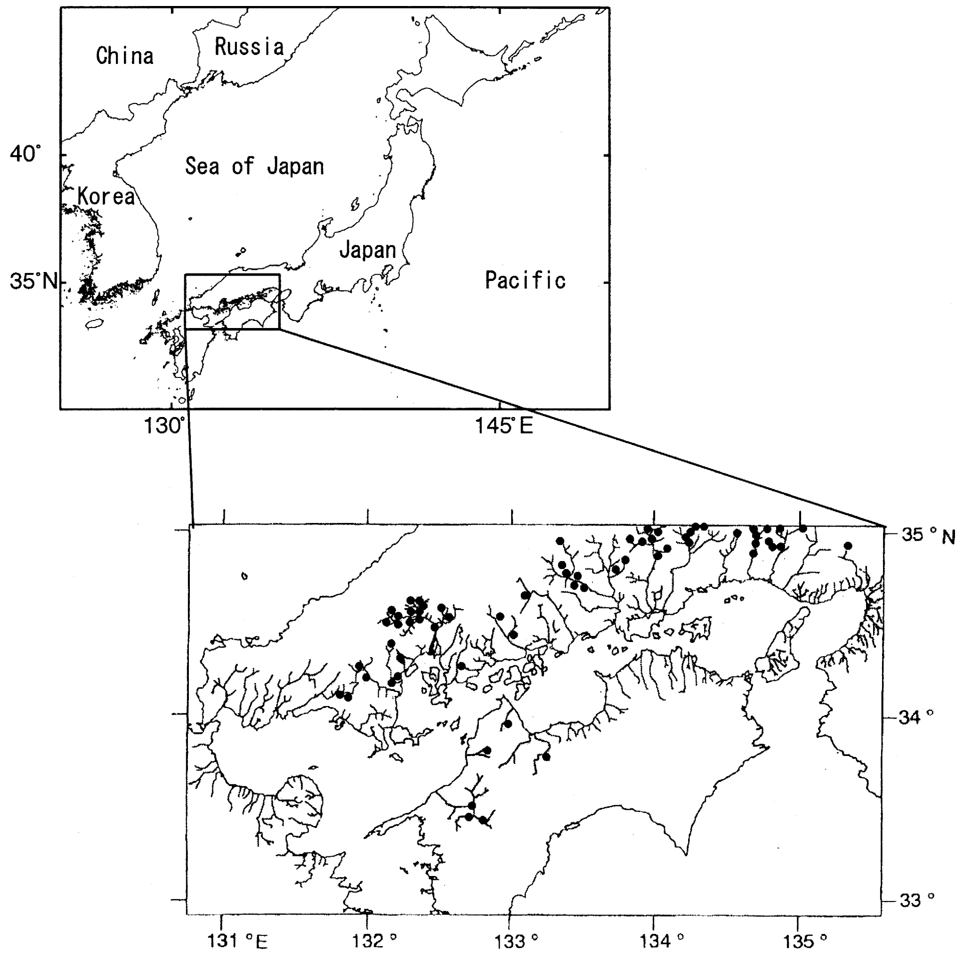

Fig. 1. Map showing the location of the Seto Inland Sea, Japan. Enlarged map shows the site of rivers with dams for hydroelectric power generation.

have become the subject of legislation. As a measure to alleviate such cultural eutrophication, a special law was established tentatively in 1973, by which the discharge of organic substances in terms of chemical oxygen demand (COD) was restricted. This tentative law was revised in 1979 as the Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea. Along with the regulation of COD from the effluent, a directive regarding phosphorus reduction was officially put in place at the same time. With the establishment of this law and the directive, STPs and sewer systems in this area have rapidly made adjustments to suit these new rules.

In the present paper, I would like to show that the present status of the Seto Inland Sea of Japan could be subject to cultural oligotrophication as a consequence of the hasty eutrophication measures in the last two decades in addition to the existing enormous number of dams (Fig. 1). The administrative-guided systems for monitoring freshwater and seawater have been well organized in Japan. The long-term data sets documenting both the eutrophication and the recovery processes presented here would be very informative for not only scientists but also managers and those concerned with environmental issues in estuaries.

2. Materials and methods

Data regarding the discharged loads of total phosphorus (TP) and total nitrogen (TN) into the Seto Inland Sea were cited from Sekine and Ukita (1997) and SECA (2001), and the long-term trends in the TN:TP ratio in the discharged water were analyzed. Data regarding TN and TP concentrations in the seawater of the inland sea were cited from SECA (2001). The number of red tide occurrences and the species composition observed in the inland sea was cited from SFCO (1974–1999); from this data the changes in the area's species composition was extracted. These analyses show the historical change in water quality and its effect on phytoplankton species composition in the entire inland sea during the last two decades or before. Data regarding fishery production was also cited from SECA (2001) and was compared to the discharged TP load.

Locations of dam sites were cited from brochures issued by the Kansai Electric Power Co. Inc. and Chugoku Electric Power Co. Inc. and from the Internet home page of the Shikoku Electric Power Co. Inc. (Fig. 1).

3. Results and discussion

3.1. Consequences of the eutrophication measures

In the Seto Inland Sea of Japan, the progress of eutrophication has caused the number of red tides to increase exponentially during the 1960s and 1970s, peaking in 1976 at $\approx$300 yr^{-1} (Fig. 2a). However, after that there occurred a marked decrease in the number of red tides, showing a stable level at around 100 yr^{-1}. This is due to the effectiveness of the law and the directive that has targeted the reductions of TP and COD in the effluent water since 1979. Therefore, a trend toward the reduction of the discharged load from 1979 to the present is seen only in TP not in TN (Fig. 3a); the TP load has decreased from $\approx$80 ton P day^{-1} to nearly half that (40 ton P day^{-1}), while the load of TN remains constant showing $\approx$700 ton N day^{-1}. This resulted in an increase in N:P ratio in the effluent water from 20 in 1967 to 37 in 1994 (Fig. 3a).

TP concentration in the seawater of the Seto Inland Sea also showed a decreasing trend from $\approx$30 $\mu g\,P\,l^{-1}$ to 25 $\mu g\,P\,l^{-1}$, reflecting the measures to reduce phosphorus from the effluent water (Fig. 3b). Here again, the level of TN concentration is relatively constant in comparison to TP, being at an average of $\approx$290 $\mu g\,N\,l^{-1}$ in data. The decrease in only the phosphorus concentration in seawater resulted in the increase of TN: TP ratio from $\approx$20 at the end of 1970s to $\approx$25 at the end of the 1990s (Fig. 3b).

In our observations conducted in 1993 and 1994, the concentration of dissolved inorganic phosphorus (DIP) in the surface water was very low being less than 0.2 μg at $P\,l^{-1}$ in almost the entire area (sometimes below the detection limit of 0.01 μg at $P\,l^{-1}$) in all seasons except autumn (Yamamoto et al., 2002), which is implying that

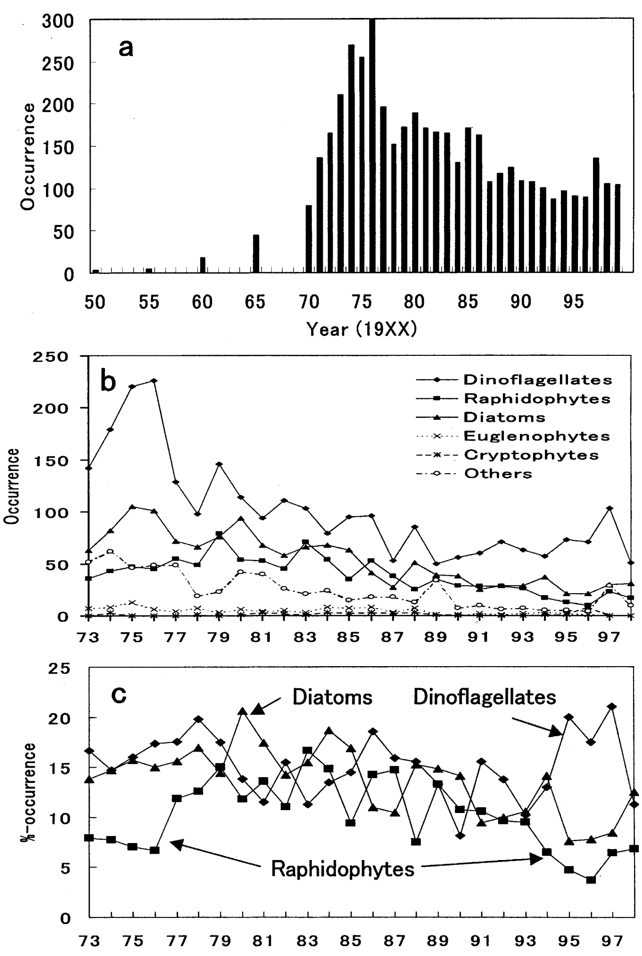

Fig. 2. (a) Variations of the number of red tide occurrence, and (b) the major taxa. (c) % occurrences of the dominant three taxa. The Seto Inland Sea, Japan. Note that the dinoflagellate *Noctiluca scintillance* is omitted from the calculation in (c) because of its heterotrophic character.

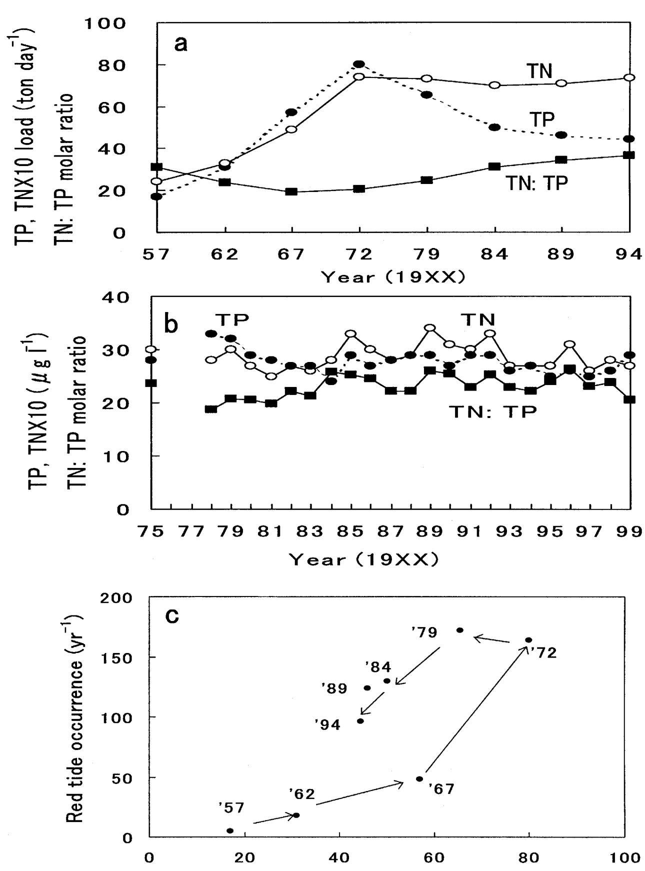

Fig. 3. Long-term variations in (a) discharged loads of TP and TN and (b) their concentrations in the seawater. TN:TP ratio is also shown. (c) is the relationship between the TP load and the number of red tides.

DIP is presumably the limiting nutrient for the growth of phytoplankton.

Interesting to note is a time lag that was found between the discharged TP load and the number of red tides (Fig. 3c). In the year of 1979, the TP load was reduced to the level of 66 ton P day^{-1} from 80 ton P day^{-1} in 1972. However, the number of red tides increased to 172 yr^{-1}. Although the number of red tides has decreased with decreasing of the TP load from 1979 to 1994, the number has not reached to the level before 1960s. This hysteresis-like pattern may be come from the length of the material circulation in the semi-enclosed system. Takeoka (1991) estimated the average residence time of the water in the Seto Inland Sea is 1.2 years, and discussed that the average residence time of nitrogen may be twice as long as that of the water due to the coupled effect of the flow having vertical shear and biochemical processes. Accumulation of organic-rich materials on the sea floor would be the one of the major causes of the delay in purification of the system.

It should be noted that fishery production has also declined with the phosphorus removal from mid-'80s (Fig. 4a; SECA, 2001; Yamamoto, 2002). Interesting to note is a time lag that was found between the discharged TP load and fishery production (Fig. 4b). Until 1972 in the course of eutrophication, the fish catch had linearly increased with increases in the TP load, whereas the increase in the number of red tides had damaged the fish culture (cf. Fig. 3c). In 1972–1984, which was the initial stage of phosphorus reduction, the fish catch still showed a slight increase. Following this period, the fish catch collapsed sharply from 1984 to 1994. From this relationship, we can say that fishery production could be regarded as a critical condition reflecting the oligotrophication due to the hasty phosphorus reduction.

This kind of hysteresis between the increase and decrease in nutrient load and fish production has been predicted through the use of a numerical model (Scheffer, 1989), and is now confirmed by the long-term data from the Seto Inland Sea. The one-year time lag in the response of chironomid fauna to a change in phytoplankton production has also observed in Lake Balaton, Hungary (Specziár and Vörös, 2001). The time lag between nutrient loading and fishery production found in the Seto Inland Sea is much longer, showing at least 5 years from 1979 to 1984. This might be dependent on the number of trophic levels, as a shorter lag was found between the TP load and the number of red tides in Fig. 3c. These time lags in response between trophic levels could also be related to a change or shift in food web structure as described below.

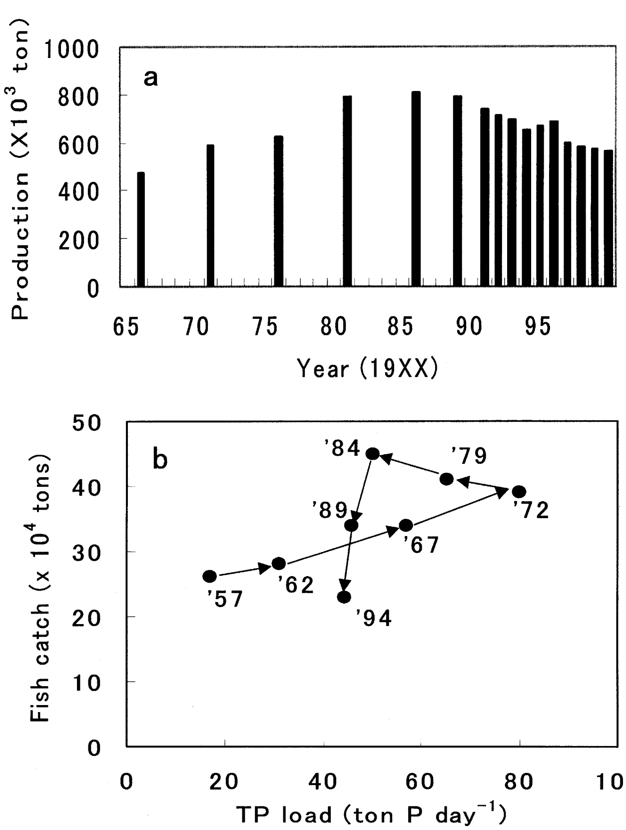

Fig. 4. (a) Variation in total fishery production including bivalve and seaweed harvesting and their cultures other than fish catch. (b) Relationship between discharged load of TP and the fish catch.

3.2. Possible changes in food web structure

It is known that the change in nutrient supply ratio can alter the species composition of a phytoplankton community (Schindler, 1977; Tilman et al., 1982). The change in phytoplankton species composition, in turn, can change the food web structure in the system. The monitoring data regarding red tides shows that the major red tide forming taxa in the Seto Inland Sea are diatoms, raphidophytes, and dinoflagellates (Fig. 2b). Out of these three groups, diatoms had dominated in late '70s to early '80s, and raphidophytes had become significant in the mid-'80s. In the 1990s, these were replaced by dinoflagellates (Fig. 2c).

Some recent studies focused on the preference of phosphorus compounds in individual phytoplankton species show evidence that some diatom species such as *Skeletonema costatum* and raphidophyte species such as *Chattonella antiqua* utilize DIP exclusively (Yamaguchi and Matsuyama pers. comm.; Matsuyama et al., 1997). These two species are the major composites of the red tides, which have been formed in the Seto Inland Sea. On the other hand, dinoflagellates such as *Alexandrium tamarense* and *Gymnodinium catenatum*, the representative harmful species that have occurred recently, prefer dissolved organic phosphorus (DOP) rather than DIP (Oh et al., 2002). As mentioned above, the DIP concentration in the surface seawater of the Seto Inland Sea showed levels of depletion in January and June of 1994.

Therefore, it could be concluded that the depletion of DIP in the seawater could have promoted the recent blooms of dinoflagellates that can utilize DOP instead of DIP.

Since most dinoflagellate species grow slowly compared to diatoms and raphidophytes, transfer efficiency could be lowered in the dinoflagellate-dominated ecosystem. Moreover, some of dinoflagellate species contain a toxin, which can be rejected as feed by consumers such as copepods. This could be an implicit cause of the decline in the fishery production. Uye et al. (2002) demonstrates that the jellyfish population has been booming in recent years. This might indicate a cascading alteration of the food web structure from a productive classical food web, in which usually rich fish production is sustained by ample copepod reproduction based on high primary production by diatoms, to probably poor fish production with a large amount of inedible jellyfish, dominated by dinoflagellates, and a less abundant copepod population.

3.3. Effects of dam construction

Another possible factor which has led the oligotrophic state of the Seto Inland Sea estuaries could be the construction of dams. Once river water is impounded by a dam, algal blooms will occur in the reservoir because of the stagnation of the flow. At this time, dams trap nutrients as particulate forms on the bottom of reservoirs as a result of the sedimentation of microalgae, thereby discharging nutrient-depleted water. Significantly, it is supposed that 10 years or more after the beginning of the impoundment both the primary production and nutrient concentration in the reservoir will be diminished to levels lower than before the impoundment, as represented by TP concentration (Stockner et al., 2000). At the same time, fishery production will also decrease to very low level. The above researchers called these sequential phenomena "boom" and "bust".

Furthermore, it is well known that, in the case of the Black Sea phytoplankton, diatom dominancy was replaced by dinoflagellates after the dam construction, mainly due to Si-depletion, because of the lower decomposition rate of diatom silica cells than the phosphorus and nitrogen contained in the cells (Humborg et al., 1997). They have also reported that the similar situation was observed in the Baltic Sea (Humborg et al., 2000). This suggests that the dam construction would not only directly decrease the productivity in the downstream water mass but also indirectly decrease productivity through the change in food web structure due to the alteration of phytoplankton species composition.

A large number of dams have been constructed in the upstream of rivers in the Seto Inland Sea region (Fig. 1). The dots plotted in Fig. 1 are only the major dams created for hydroelectric generation. In addition to these, there are many small impoundments along the rivers for other purposes. Thus, such a large number of dams could have accelerated the alteration of the Seto Inland Sea ecosystem through the decrease in the amount of nutrient supply from the land and probably by the change in the elemental ratio in the discharged water.

4. Conclusion and proposal

The processes assumed to have occurred in the entire Seto Inland Sea are summarized in Fig. 5. The measures instituted to reduce phosphorus load have been successful as proven by the decrease in the number of red tides. However, these measures appear to have reduced the sea's primary production as a whole, and changed the phytoplankton species composition due to the increase in the N:P ratio in the discharged water and in the seawater as well. These factors could have caused the decline in fishery production.

A large number of dams could also have had negative effects on fishery production through the decrease in nutrient discharge, particularly silicate. As a result, the present condition of the Seto Inland Sea is clearly oligotrophic in the sense that it is an example of "cultural oligotrophication". As shown in Fig. 4, I would say that the condition of the ecosystem of the Seto Inland Sea is critical in regard to fishery production.

Recently, nitrogen has been selected as another element to be reduced, and the amount of discharge is going to be restricted officially by the law beginning in

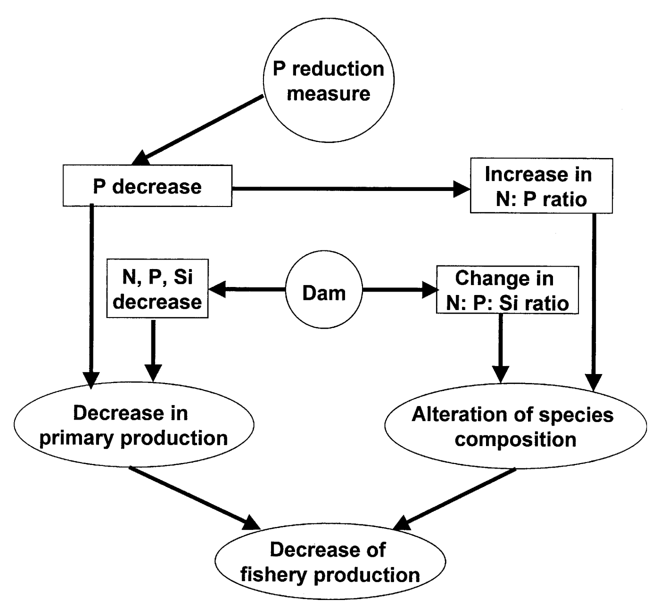

Fig. 5. Processes presumed to have occurred in the course of phosphorus reduction during 1980s and 1990s in the Seto Inland Sea, Japan.

the year of 2002. In light of this, there should be much more discussion regarding the elemental balance in the discharged water. In order to maintain the health of the ecosystem of the Seto Inland Sea and to support sustainable fishery production, I propose that nitrogen, phosphorus, and silica levels and their ratio should be controlled in the proper proportions, which means a joint N-, P-, and Si-control as proposed by Smith (1998), involving a dual N- and P-loading reduction. Although much discussion will be needed by the stakeholders in order to define the proper nutrient loading level for each local region, the elemental ratio should be established by scientists. The Redfield ratio (N:P:Si = 16:1:15), which has been regarded an average composition of phytoplankton cells (Redfield, 1934; Dugdale and Wilkerson, 1998), could temporarily be adopted as the elemental ratio in the discharged water, although each species has its own optimum elemental ratio for growth. One possible way to regulate the levels and the elemental ratio of nutrients in the seawater is by artificially controlling the amount, the timing, and the interval of the discharged water from dams and STPs if managers and stakeholders can agree on this idea based on estuarine ecology.

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